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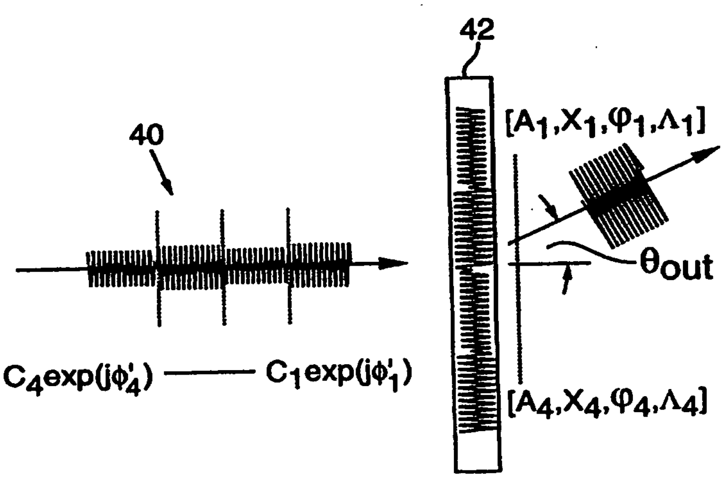

(57) Abstract

Methods and apparatus are disclosed that apply a predetermined complex–valued spectral transfer function to an input optical field to produce an output field that propagates in an output direction. Methods for making such apparatus are also disclosed. Segmented gratings (1915, 1916, 19a15, 19a16) fabricated according to one example comprise a series of spatially distinct subgratings arrayed end to end. Each subgrating possesses a periodic array of diffraction structures, such as lines or other elements. The transfer functions of such segmented gratings are determined by controlling (a) the spatial periodicity or frequency of each subgrating, (b) the amplitude of each subgrating, (c) the spacing between the last diffraction structure (or line) on each subgrating and the first diffraction structure (or line) of the successive subgrating, and (d) the optical path length and transparency through each subgrating, or each subgrating plus additional material layers utilized to control optical path length and transparency. Communication systems using such segmented gratings are also provided.

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SEGMENTED COMPLEX DIFFRACTION GRATINGS

Field of the Invention

The invention relates to optical communication systems using segmented complex diffraction gratings.

Background

Many optical communication systems use wavelength division multiplexing (WDM) to increase the data rate available with a single optical fiber. Other optical communication systems offer increased data rates using optical code division multiple access ("OCDMA"). OCDMA systems encode different communication channels with different temporal codes as contrasted to WDM systems in which different channels use different wavelengths.

U.S. patent 5,182,318 and U.S. patent application 09/227,097 describe diffraction gratings having a complex profile that include multiple sinusoidal subgratings, each subgrating having a specific amplitude and spatial phase. Such gratings can deflect optical pulses from a specific input direction to a specific output direction while simultaneously multiplying the Fourier spectrum of the input pulse by a predetermined filtering function. The output signals are a cross-correlation between the input waveform and the grating encoded temporal waveform. These gratings can accept input beams and generate spectrally filtered output beams propagating in one or more output directions. The filtering function of the device is programmed by choice of grating profile. By suitable programming, multiple transfer functions may be realized, each having its own specific input and output direction.

Summary of the Invention

According to an aspect of the invention, optical apparatus (such as, for example, a segmented grating) are disclosed that apply a predetermined complex-valued spectral filtering function to an input optical field and produce a filtered version of the input field that propagates in an output direction. Another aspect of the invention includes methods for making such optical apparatus. Grating devices, comprised of one or more such optical apparatus, can be used, for example, in OCDMA data links to temporally code optical signals with specific codes such that multiple coded channels simultaneously can be transmitted through the same link and then be decoded into separate channels at the output of the system. The optical apparatus also can be used for programmable spectral filtering.

In a further aspect of the invention, segmented gratings comprise a series of spatially distinct subgratings arrayed end to end. Each subgrating possesses a periodic array of diffraction structures (lines or more general elements). The overall transfer function of such a segmented grating is determined by controlling (a) the spatial periodicity (spatial frequency) of each subgrating, (b) the amplitude of each subgrating, (c) the spacing between the last diffraction structure on each subgrating and the first diffraction structure of the successive subgrating, and (d) the optical path length and transparency through each subgrating, or each subgrating plus additional material layers utilized to control optical path length and transparency.

statique ou dynamique?

Brief Description of the Drawings

FIG. 1A is a schematic diagram of a multiplexed communication system.

FIG. 1B is a schematic diagram of an optical path of FIG. 1A.

FIG. 2A is a plan view of a segmented grating.

FIG. 2B shows an elevational sectional view of the segmented grating of FIG. 2A.

FIG. 3A is a schematic diagram showing an input angle and an output angle for a light beam incident to the segmented grating of FIGS. 2A-2B.

FIG. 3B is a schematic diagram showing an angle between a plane containing an input light beam and an output beam and an x-axis wherein the angle is measured in an x-y plane.

FIG. 3C shows a temporally coded optical pulse having four time slices that is incident on a segmented grating having four contiguous, equal-width subgratings.

FIG. 4 illustrates a method for fabricating segmented gratings.

FIG. 5 illustrates another method for fabricating segmented gratings.

FIG. 6 illustrates another method for fabricating segmented gratings.

FIG. 7 is a sectional view of two subgratings of a segmented grating, the subgratings having different optical thicknesses.

FIG. 8 is a sectional view of two subgratings of a segmented grating, the subgratings having a saw-tooth shaped blaze.

FIG. 9 is a schematic diagram of a four-channel OCDMA system.

Detailed Description

FIG. 1A is a schematic diagram of an OCDMA communication system 9 that uses segmented diffraction gratings to perform optical multiplexing and demultiplexing. A short-pulse laser 10 generates a coherent light beam 12. A beam splitter 13 divides

the light beam 12 into beams 15, 16. The beams 15, 16 are modulated by respective modulators 15a, 16a, thereby generating respective modulated beams 15b, 16b. The modulation of each of the beams 15a, 16a is done in response to external data streams, not shown in FIG. 1A. The beams 15b, 16b consist, either by virtue of the operative character of the laser source 10, the action of the modulators 15a, 16a, or a combination of the two, of a stream of bits whose temporal character matches the designed input pulses of a compound grating 19.

Each of the beams 15b, 16b is directed at the compound grating 19 so that it is incident on the compound grating 19 at an angle that differs for each beam. The compound grating 19 comprises two superimposed segmented gratings 19_{15}, 19_{16} (not shown in FIG. 1A) operative on the beams 15b, 16b, respectively, to produce separate output time codes in an optical transport 11 (such as, for example, an optical fiber) for each of the beams 15b, 16b. (The coding technique and the details of the compound grating 19 are described below). The combined coded beam is transported to a second compound grating 19a via the optical transport 11.

The compound grating 19a also comprises two superimposed segmented gratings $19a_{15}$, $19a_{16}$ (not shown in FIG. 1A) operative on the time codes in the beam received from the optical transport 11 to produce respective output beams 15c, 16c. The beams 15c, 16c are modulated identically to the beams 15a, 16a, respectively. (The decoding technique and the compound grating 19a are described below). The beams 15c, 16c are detected by detectors 15d, 16d and converted into electrical signals that correspond to the signals that activated the modulators 15a, 16a.

As shown with respect to the communication system 9 of FIG. 1A, two beams are combined (multiplexed) into one coded beam that propagates along an optical transport. In other such systems, three, four, or more beams can be multiplexed into one beam. The combined coded beam can be transmitted over a transmission system and then the beams can be demultiplexed.

FIG. 1B illustrates the transmission of the beam 16b through the communication system 9 of FIG. 1A. The beam 16b is collimated by a lens 6a so that the beam 16b illuminates the entire operative width of the two-dimensional segmented grating 19_{16} contained within the compound grating 19. (The compound grating 19 also includes the segmented grating 19_{15}.) As shown in FIG. 1B, the compound grating 19 comprises the segmented gratings 19_{15}, 19_{16} that correspond to different surfaces of the compound grating 19. In other embodiments, such segmented gratings can be combined into a single layer on a single surface, the optical properties of the single layer determined by summing the optical properties of individual subgratings.

A second lens 6b focuses the beam 16b into the optical transport 11. Spatial filtering provided by a spatial filter 8a (or produced by entry into the optical transport 11) selects an operative angular output channel of the segmented grating 19_{16}. After transmission through the optical transport 11, a lens 7a receives the beam 16b and illuminates the segmented grating $19a_{16}$ over its operative width and the beam 16c transmitted through the compound grating 19a is focused by a collimating lens 7b. A spatial filter 8b following the lens 7b selects the operative output angular channel of the segmented grating $19a_{16}$. The compound grating 19a also comprises the segmented gratings 19_{a15} for the beam 15b (not shown in FIG. 1B) and the segmented gratings 19_{a15}, 19_{a16} can be on different surfaces or superposed. FIG. 1B illustrates only the path of the beam 16b but the path of the beam 15b can be similar.

The communication system 9 includes mechanisms for collimating each of the beams 15b, 16b, and providing for the beams to illuminate corresponding segmented gratings 19_{15} and 19_{16} within compound grating 19 at a different angle. A separate lens, such as the lens 6a, for each input beam provides an exemplary mechanism for collimating beams and illuminating segmented gratings. Alternatively, a single lens and control over the launch conditions of the input beams toward the single lens can be used. An example of spatial control comprises a spatial filter in the front focal plane of the single lens with apertures sufficiently small to provide diffractive grating filling. At the output of the compound grating 19a, there is a mechanism for providing a spatial Fourier decomposition of the angular output of the segmented gratings comprising compound grating 19a and appropriate spatial filtering mechanisms for selecting the multiple operative angular output channels, e.g., the lens 7b and the spatial filter 8b. A single lens provides an exemplary mechanism for providing spatial Fourier decomposition. Apertures placed in the focal plane of the single lens then permit selection of operative angular channels. Other methods for selecting operative angular channels also can be used.

The compound gratings 19, 19a through their constituent segmented gratings 19_{15}, 19_{16} and $19a_{15}$, $19a_{16}$, respectively, are designed to accept light beams from one or more directions and to redirect the light beams into one or more output directions in a manner that is dependent on the temporal waveform of the light beams. Considering a specific input direction and one of the output directions associated with this specific input direction, the grating's functions are summarized as follows. A portion of each spectral component of the input light beam is mapped into the output direction with a controlled amplitude and phase. The compound grating applies a designated complex valued spectral transfer function to the input light beam and produces a filtered version

of the input light beam that propagates in the output direction. The spectral resolution of the filtering function is determined by the physical size of the corresponding segmented grating and the input and output angles of the light beam relative to the grating. The spectral mapping between each input direction and each output direction may be programmed substantially independently using dedicated segmented gratings for each mapping. Such mappings are described in U.S. patent 5,182,394 which is incorporated herein by reference. In the communication system 9 of FIG. 1A, the spectral transfer functions are determined by respective segmented gratings.

FIG. 2A shows an example of a segmented grating 20 that is similar to the segmented gratings 19_{15}, $19a_{15}$, 19_{16}, $19a_{16}$. (The compound gratings 19, 19a each contain two such segmented gratings, superimposed or summed together.) The design of a single segmented grating is described below and compound gratings incorporating two or more segmented gratings are designed through repetitive application of single segmented grating procedures.

The segmented grating 20 has N spatially distinct subgratings 20_i for $i = 1$ to N, where $N = 8$. In other embodiments N can be less than or greater than eight. FIG. 2B is a sectional view of the segmented grating 20. As shown in FIG. 2B, each of the subgratings 20_i have amplitude, phase, and period, all of which can be independently selected for each of the subgratings 20_i. (FIG. 2B shows only six at the subgratings 20_i.) The structure of the subgratings 20_i is defined mathematically with respect to coordinate axes 22 and angles descriptive of the segmented grating 20 and associated optical input and output directions. For convenience, the origin of the coordinate axes 22 is selected to be at a center 23 of the segmented grating 20. The segmented grating surface is taken to coincide with the x-y plane. With reference to FIG. 3A, an input line 31 passes through the coordinate center 23 and is parallel to an input direction and an output line 33 passes through the coordinate center 23 parallel to an output direction. The input line 31 and the output line 33 define a plane, referred to herein as the input/output plane. In the mathematical description used herein, the z-axis is located in the input/output plane. In other embodiments, the z-axis is not in the input/output plane.

FIGS. 3A and 3B show an input angle (θ_{in}) and an output angle (θ_{out}) that are in the input/output plane. The angular separation between the input (output) direction and the z-axis is θ_{in} (θ_{out}), where the angles are positive as shown in FIG. 3A. FIG. 3B shows an angle θ_a between the input/output plane and the x-axis as measured in the x-y plane. Thus, FIGS. 3A and 3B show the geometrical arrangement of a segmented grating relative to particular input and output optical field directions. For the segmented

grating 20, a groove-normal line is defined as a line perpendicular to the grooves lying in the plane of the segmented grating surface and passing through the origin. As described above, the groove-normal line is contained within the input/output plane and is parallel to the x-axis. In other embodiments, the groove-normal line can be at other locations relative to the input/output plane.

When the input/output plane contains the z-axis, the diffractive structures (grooves) that redirect and spectrally filter the input optical beam into the output direction are perpendicular to the input/output plane and are within or on the surface of the segmented grating 20. Multiple segmented gratings having the same or different values of θ_a can be co-located on the same substrate with any degree of overlap. Compound gratings may include a single segmented grating, multiple spatially superimposed segmented gratings, or a combination of spatially superimposed and spatially separated segmented gratings fabricated onto a single substrate.

The compound grating 20 uses transmissive segmented gratings, but reflective gratings can also be used. Each input optical beam illuminates the active width of each segmented grating structure with which it is intended to interact. Referring to FIGS. 1A-1B, the compound grating 19 and the segmented gratings 19_{15}, 19_{16} are substantially planar and arranged parallel to the x-y coordinate plane. As in the case of simple monospaced diffraction gratings, segmented gratings may be implemented with nonplanar surface geometry. For example a segmented grating could be supported by a nonplanar (e. g., a concave or convex) substrate. The use of non-planar surface geometry allows for the control over the spatial wavefront of input optical beams in addition to the spectral content control that is afforded by grating segmentation.

A single segmented grating is fabricated in the form of a series of N spatially distinct subgratings arrayed side to side whose collective span defines the operative width of the segmented grating. If the input/ouput plane contains the x-axis, each subgrating possesses a periodic array of diffractive structures (for example, grooves) arranged in a plane perpendicular to the input/output plane. The spacing between diffractive structures within the N successive spatial subgratings is typically but not necessarily the same. The N subgratings are written or otherwise created such that each occupies a specific subsection of a compound grating surface and subgratings appear successively as one passes along the groove-normal line. The subgratings of a particular segmented grating typically (but not necessarily) have the same span, perpendicular to the groove-normal line, i.e., height. The spatial interval between the last diffractive structure (groove) of each subgrating and the first diffractive structure (groove) of the successive subgrating can be controlled as well, as described below.

Control over groove positioning provides control over relative spatial phase of adjacent subgratings. Also controlled is the amplitude of the diffractive structures within a given subgrating. The manner in which subgrating spacing and amplitude is controlled determines the spectral transfer function of the grating. The optical thickness of the various subgratings comprising a segmented grating can be controlled by variation of substrate thickness, addition of phase masks, or other means known in the art to provide additional control over the spectral transfer function of the grating. Variation of optical thickness under a spatial subgrating or the separation between subgratings both act to control the relative phase of light transferred from the input to the output directions. Active devices can be added between the subgratings to dynamically change subgrating-subgrating separation to allow for the dynamical reprogramming of the spectral filtering function. Active devices to control the optical thickness of subgratings inclusive of overlays can be added to provide an alternative means of dynamical reprogramming of the spectral filtering function.

The representative segmented grating shown in FIGS. 2A-2B has eight subgratings 20_i. The subgratings 20_i have essentially equal extent along the groove normal line; however, subgratings of dissimilar extent can be employed. The segmented grating 20 is a transmissive phase grating, but it could be a reflective, amplitude, or other generalized physical grating type.

We represent the transmissive optical phase shift versus position of a subgrating 20_i as

$$h_i(x') = A_i f_i(2\pi(x' - x_i)/\Lambda_i) + \varphi_i \qquad \{\text{for } x_i^a \le x' \le x_i^b\}, \qquad (1)$$

where x' represents the spatial position coordinate along the groove-normal line, x_i is the spatial position shift of the i[th] subgrating groove pattern, the function f_i represents a particular groove profile and is periodic with period 2π and modulates between the values of 0 and 1, φ_i is an optical phase shift introduced by a variation in substrate thickness or superimposed phase mask, A_i is a real-valued amplitude factor, x_i^a and x_i^b are the edge positions of subgrating i, and Λ_i is the spatial period of the i[th] subgrating. Outside the prescribed spatial interval, $h_i(x') = 0$. The subscript i ranges from 1 to N and denotes individual subgratings. By specifying the parameters A_i, φ_i, x_i, and Λ_i for the subgratings employed, a wide range of spectral filtering functions can be encoded.

The parameters A_i, φ_i, x_i, and Λ_i necessary to produce specific, predetermined spectral transfer functions are chosen in a variety of ways. For example, a segmented grating can be constructed to provide a predetermined spectral transfer function T(ν) (where ν is the optical frequency) as approximated by N transmission coefficients each of which corresponding to one of N contiguous frequency channels collectively

spanning the full non-zero width of $T(\nu)$, where $T(\nu)$ is non-zero over a specific spectral region of width $\delta\nu$ centered about the frequency ν_0. To approximate $T(\nu)$ to accomplish this purpose, the segmented grating requires approximately N subgratings. To provide filtering with a predetermined resolution, the subgratings require a spatial width of approximately $c/[\delta\nu(\sin\theta_{in} + \sin\theta_{out})]$, where c is the vacuum speed of light. The total width of the grating is given approximately by $Nc/[\delta\nu(\sin\theta_{in}+\sin\theta_{out})]$, assuming that the subgratings are contiguous. For example, if $\delta\nu$=100 GHz, $\theta_{in} = 0°$, $\theta_{out} = 45°$, and N = 8, the complete spatial width of the segmented grating for $T(\nu)$ is approximately 3.4 cm.

The parameters (A_i, φ_i, x_i, and Λ_i) for all of the N subgratings comprising the segmented grating determine the spectral transfer function $T(\nu)$. Given the subgrating parameters, the spectral transfer function of the segmented grating can be determined. Conversely, given a predetermined spectral transfer function, the subgrating parameters necessary to create a corresponding segmented grating can be determined. It should be understood that, while the mathematics presented herein contain certain constraining assumptions in order to facilitate explanation, the equations can be generalized.

An expression for the spectral transfer function $T(\nu)$ exhibited by a segmented grating in terms of subgrating parameters is given first. Under the assumptions that (1) $A_i << 1$ or $A_i = A$ = constant, (2) the grating output is either plus or minus first order ($m = \pm 1$), and (3) the N subgratings have equal spatial width ($d = x_i^b - x_i^a$ = constant), equal spatial period ($\Lambda_i = \Lambda$ = constant), and are contiguous, the spectral transfer function $T(\nu)$ of the segmented grating may be written as a sum over subgrating parameters as follows:

$$T(\nu) = F(\nu)\sum_{i=1}^{N} a_i \exp(j\Phi_i) \tag{2a}$$

where:

$$a_i = A_i \exp(j(\varphi_i - 2\pi x_i m/\Lambda)), \tag{2b}$$

$$\Phi_i = \pi(x_i^a + x_i^b)(\beta\nu - m/\Lambda), \tag{2c}$$

and

$$\beta = (\sin\theta_{in} + \sin\theta_{out})/c. \tag{2d}$$

$F(\nu)$ is the spatial Fourier transform of a subgrating,

$$F(\nu) = \frac{jC}{N}\operatorname{sinc}(\pi d(\nu\beta - m/\Lambda)), \tag{2e}$$

where j is $\sqrt{-1}$, and C is a constant dependent on the groove profile and contains a phase factor dependent on the choice of x'-origin. The function sinc(x) = sin(x)/x. In writing Eqs. (2a)-(2e), it is assumed that the output signal is derived from the plus (m = 1) or minus one (m = -1) diffractive order of the subgratings. Analogous expressions for higher (positive and negative) orders can also be obtained.

To design a segmented grating having a specific transfer function, parameters for each subgrating are determined. To do this, Eq. (2a) is solved for a_i to obtain

$$a_i = \beta d \int_{m/(\beta\Lambda)-1/(2\beta d)}^{m/(\beta\Lambda)+1/(2\beta d)} \frac{T(\nu)}{F(\nu)} \exp(-j\pi(\nu\beta - m/\Lambda)(x_i^a + x_i^b))d\nu \qquad (3)$$

From Eq. (2b), A_i is equal to the amplitude of a_i. The quantities x_i and φ_i both determine the phase of a_i as seen in the above equations. An appropriate combination of x_i and φ_i consistent with Eq. (2b) and Eq. (3) can be chosen at the convenience of the grating designer. The parameter Λ is chosen so the light of carrier frequency ν_o is maximally diffracted from θ_{in} to θ_{out} using the well-known grating equation $sin(\theta_{in}) + sin(\theta_{out}) = m\lambda_o/\Lambda$ where $\lambda_o = c/\nu_o$ is the center wavelength of the desired transfer function. The angles θ_{in} and θ_{out} are designer inputs as is T(ν). Mathematically speaking, Λ is chosen as the solution of the mathematical equation $\beta\nu_o\Lambda = m$.

Alternatively, a more general solution for obtaining the subgrating parameters is to calculate the continuous grating profile that will generate the desired continuous transfer function. If the transmissive phase of a grating as a function of x' is given by

$$h(x') = -j\ln\left[\sqrt{2\pi}\beta D \int_{-\infty}^{+\infty} T(\nu)\exp(-j2\pi\beta\nu x')d\nu\right], \qquad (4)$$

the spectral transfer function of the grating in direction θ_{out} will be T(ν), where D is the width of the grating. Again θ_{in}, θ_{out}, and T(ν) are designer inputs. It is necessary to convert the continuous transmissive phase profile given by Eq. (4) to a segmented phase profile consistent with subgrating fabrication. Parameters descriptive of constant phase segments which can be directly mapped onto the parameters defining constituent subgratings can be determined as follows: The continuous surface phase profile *h(x')* generally consists of a carrier spatial modulation with a slowly varying amplitude and phase shift. A representative average of the spatial phase shift over the physical extent of subgrating *i* is determined and the values of φ_i and x_i are adjusted in a convenient combination to match the determined spatial phase shift determined from Eq. (4). Similarly, a representative value of the grating amplitude from Eq. (4) within

the physical extent of subgrating i is determined and A_i is set equal to this grating amplitude. The spatial period Λ_i is set equal to the carrier modulation period of *h(x')* as given by Eq. (4). A variation to the approach just given is to determine a spatial carrier, amplitude, and phase within the extent of each subgrating separately. This procedure allows for the variation of Λ_i from subgrating to subgrating.

For a segmented grating to perform the function of optical cross-correlation between optical input waveforms and a reference optical waveform, the grating's spectral transfer function should be the complex conjugate of the spectrum of the reference optical waveform. The function of optical cross correlation here means that the electric field emitted by the grating in the operative output direction represents the temporal cross correlation between (a) an input optical waveform incident on the grating along the operative input direction and (b) the specific reference optical waveform whose conjugated spectrum coincides with the grating's spectral transfer function.

Consider a reference optical waveform such as an optical pulse whose time profile is represented as a sequence of M contiguous time slices within which the amplitude and phase of the optical field are constant. In each time slice i (for i = 1,..,M), the electric field has constant amplitude B_i and phase ϕ_i. The reference waveform is thus determined by the set of complex numbers $[B_1\exp(j\phi_1), B_2\exp(j\phi_2),\ldots,B_M\exp(j\phi_M)]$ along with the optical carrier frequency in each time slice and the overall temporal duration of the waveform. FIG. 3C schematically illustrates a temporally coded optical pulse 40 of the form $[C_1\exp(j\phi'_1), C_2\exp(j\phi'_2), C_3\exp(j\phi'_3), C_4\exp(j\phi'_4)]$ incident to a segmented grating 42.

When an optical waveform is incident on a grating such as the segmented grating 42, the segmented grating 42 spectrally filters the incident waveform as described by the grating spectral transfer function for the particular θ_{in} and θ_{out} employed. If the segmented grating is to perform the function of cross-correlation against the reference optical waveform, the subgratings should have parameters that are the "time-reversed" complex conjugate of the reference optical waveform. For example, for a segmented grating having eight segments, such that

$$[a_1, a_2,\ldots, a_8] = [B_8\exp(-j\phi_8), B_7\exp(-j\phi_7),\ldots,B_1\exp(-j\phi_1)],$$

the subgrating parameters are related to a_i by equation (2b) given the assumptions in deriving Eqs. (2a)-(3) are met. The operation of cross-correlation may be used to multiplex and demultiplex optical signals.

The diffraction efficiency of a grating segment depends upon the groove profile of the segmented grating. The magnitude of the spectral transfer function and the constant C of Eq. (2e) depend on the diffraction efficiency.

The following specifies the compound gratings 19, 19b employed in the communication system 9 of FIG. 1A. As noted above, the compound gratings 19, 19a comprise two superimposed segmented gratings, 19_{15}, 19_{16} and $19a_{15}$, $19a_{16}$, respectively. The compound grating 19 accepts uncoded data streams and launches time-coded data into a common channel. The compound grating 19a accepts time-coded data and launches distinct time codes into distinct output directions while simultaneously stripping off time-coding. The compound grating 19a functions through the process of cross-correlation. In an example, the compound gratings 19, 19a each comprise two superimposed segmented gratings 19_{15}, 19_{16} and $19a_{15}$, $19a_{16}$, respectively, and the net transmissive optical phase shift versus position is consequently the sum of the transmissive optical phase shift functions for the two segmented gratings. In an example, the groove profile is a square (square-wave) groove profile with a fifty percent duty cycle. The subgrating amplitudes are $A_i = \pi/2$ for the first and second segmented gratings, the diffraction efficiencies of the compound gratings 19, 19a are approximately 20% in the operative output directions. If such a transmission grating is to be etched into a substrate with optical index $n_o = 1.50$, the etch depth that corresponds to $A_i = \pi/2$ phase modulation is given by 0.77 μm for a carrier wavelength of 1.54 μm. In this example, the input-output plane contains the z-axis. The compound gratings 19, 19a have eight subgratings, and each subgrating has a width of 1 mm; thus the total grating width is 8 mm. The segmented gratings 19_{15}, 19_{16}, $19a_{15}$, $19a_{16}$ comprising the compound grating 19, 19a have $\theta_a = 0°$ and are designed for optical data streams having the carrier frequency 195 THz (a carrier wavelength of about $\lambda = 1.54\mu m$).

The optical data channels controlled by a first segmented grating of the compound grating 19 are specified to have the input and output angles $\theta_{in} = 17.94°$ and $\theta_{out} = 0°$. The grating spacing is $\Lambda = 5$ μm for all subgratings of the first segmented grating. The first segmented grating is designed to accept temporally short input pulses of optimal duration $\Delta\tau_p = 1$ ps along $\theta_{in} = 17.94°$ and generate temporally coded pulses along the multiplexed output direction $\theta_{out} = 0°$. To produce output pulses of approximate duration $\tau_p = 8$ ps with the following temporal code

$$[1, 1, 1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j4\pi/3), \exp(j4\pi/3)]$$

the corresponding subgrating xi and φ_i parameters for the first segmented grating are $[x_1, x_2, \ldots, x_8] = [0.0\mu m, 0.0\mu m, 0.0\mu m, -1.67\mu m, 1.67\mu m, 0.0\mu m, 1.67\mu m, 1.67\mu m]$ and $[\varphi_1, \varphi_2, \ldots, \varphi_8] = [0,0,0,0,0,0,0,0]$.

The second segmented grating consists of a set of eight subgratings with the following common specifications: $\Lambda = 3\ \mu m$, $\theta_{in} = 30.89°$, $\theta_a = 0°$, and $\theta_{out} = 0°$. The second segmented grating, like the first, accepts temporally brief data bits of optimal duration $\Delta\tau_p \approx 1.71$ ps moving along its input direction and generates temporally coded bits of approximate duration $\tau_p = 13.7$ ps into its output direction. The first and second segmented gratings have a common output direction. If the coded output bits from second segmented grating are to have the following form

$$[1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j2\pi/3), \exp(j4\pi/3), 1, \exp(j2\pi/3)],$$

then the corresponding subgrating parameters of the second segmented grating are $[x_1, x_2, \ldots, x_8] = [0.0\mu m, -1.0\ \mu m, 1.0\ \mu m, 0.0\mu m, -1.0\ \mu m, 1.0\ \mu m, 0.0\mu m, -1.0\ \mu m]$ and $[\varphi_1, \varphi_2, \ldots, \varphi_8] = [0,0,0,0,0,0,0,0]$. The filtering bandwidth of the second segmented grating is $\delta\nu \cong 1/\Delta\tau_p$ or 0.6 THz.

The multiplexed beams co-propagating in the optical transport 11 are demultiplexed by the compound grating 19a. The demultiplexing compound grating 19a in FIGS. 1A-1B is identical in design to the compound grating 19. For an input angle into grating 19a of $\theta_{in} = 0°$ the demultiplexed output beams are collected in angles $\theta_{out} = -17.94°$ and $\theta_{out} = -30.89°$ for the first and second reference optical waveforms respectively. With these grating specifications, the laser 10 of FIG. 1A preferably has a maximum temporal pulse width (FWHM) of 1 ps (given by the minimum $\Delta\tau_p$ of the two segmented gratings).

Using lithography (optical or electron beam), surface profiles can be written onto a substrate point by point to make segmented gratings, and compound gratings and segmented gratings with spatial phase shifts between the subgratings can be written directly onto a transmitting or reflecting surface. Control of subgrating amplitude is also possible using this technique. In addition, a variety of holographic techniques can be used to successively or simultaneously record subgratings with controlled surface profile properties.

FIG. 4 illustrates a method of manufacturing segmented gratings (and compound gratings) by spatial repositioning of a grating substrate to produce subgratings with controlled spatial phase. The angle between the two beams or the wavelength of the two beams used in standard holographic recording can be used to control the grating period Λ_i. Spatial phase shifts may be introduced between exposures by translating a grating substrate. Thus, the N subgratings can be recorded,

as shown in FIG. 4, by spatially translating an aperture mask 45 of width d = D/N (where D is the total grating length) by its width N times and exposing the recording material at each mask position. Between exposures, the grating substrate is shifted along the groove-normal line. The substrate shifts a distance x_i relative to a fixed reference prior to exposure of subgrating i. Control of writing beam intensity between subgrating exposures allows control of subgrating amplitudes A_i.

A similar method of producing segmented gratings comprised of subgratings with spatial phase shifts uses single exposure holography with a phase-code mask having the appropriate subgrating phase shifts encoded in its optical thickness. The mask is placed in one of the two interfering beams in close proximity to the substrate. If these beams are incident from opposite sides of the substrate, this phase-mask can be contacted directly onto the grating substrate.

FIG. 5 shows a holographic method for fabricating gratings with N subgratings with controlled spatial phase shifts. This technique controls the phase-difference, ϕ_i, between the two optical writing beams 51, 53. Control of the intensities of the writing beams 51, 53 permits control of subgrating amplitude as well. The optical phase-difference determines the position of the interference pattern on the sample where the beams overlap, and their intensity controls the modulation amplitude of the interference pattern. The subgratings are recorded by illuminating the whole sample region with the interference pattern, but using an aperture of width d so that only the region behind the aperture is exposed and recorded. By spatially shifting the aperture across the sample in N steps it is possible to write a series of N subgratings, with each grating having a phase determined by the phase-difference ϕ_i used during exposure of the i^{th} subgrating.

FIG. 6 illustrates a method of producing subgratings termed the "master phase mask" approach. In this method, a single writing beam 61 is used in conjunction with a master phase mask diffraction grating 63. The writing beam 61 incident to the master grating 63 is diffracted to yield one or more extra output beams, such as the beams 65, 67. The writing beam 61 and the diffracted beams interfere, producing an interference pattern that can be used to record a near duplicate of the master grating. This property of diffraction gratings makes it possible to use a master grating to generate the interference pattern needed for the grating. The phase in each subgrating is imparted by translating the master grating or the recording substrate between successive masked subgrating exposures.

The phase shifts φ_i can be controlled by selecting the optical thickness of the substrate. FIG. 7 shows a two-segment grating wherein the subgratings are written

onto a substrate of varying thickness. Variation in substrate thickness provides for control over the subgrating parameter φ_i . More generally, φ_i can be controlled by any of the means known in the art for varying the optical path length of the subgrating substrates. For example, index-of-refraction changes between subgrating substrates provide for control over φ_i .

A variety of fabrication methods support control over φ_i . Lithography provides for changes in surface level (and hence substrate thickness) as well as groove profile. Programmed lithographic variations in surface level thus provide control over φ_i . Holographic, lithographic, or mechanical ruling methods can be implemented on a substrate that has been prepared to have specified optical thickness throughout the spatial region occupied by each subgrating. Control over optical thickness can be achieved by any of the means known in the art including but not limited to etching and thin-film coating.

The value of φ_i for each subgrating can also be controlled through use of a separate phase mask placed over a constant thickness substrate.

A grating can also be made using a Fourier synthesis method by the superposition of multiple periodic gratings each of which spanning the entire width of the segmented grating. The constituent periodic gratings have relative phases, amplitudes, and spatial periods that, when summed, result in the segmented grating profile of interest. The constituent periodic gratings are the Fourier components of the desired grating profile. The more Fourier components used the more sharply defined the subgratings will be.

The gratings can be manufactured by holographic or lithographic methods. By exposing a photosensitive substrate with multiple holographic exposures, each of which writing a particular constituent periodic grating, the desired grating profile can be recorded. Lithographic means also provide for multipass writing wherein each pass is employed to write one constituent periodic grating.

By using lithographic and holographic methods the gratings may have an arbitrary modulation profile including a grating blaze such as a saw-tooth, square wave, sine wave, or other blaze to engineer the distribution of power into the diffraction orders. FIG. 8 is a schematic of a grating similar to that shown in FIG. 2B, but with a saw-tooth modulation profile.

It is noted that the descriptions of the segmented gratings presented in herein include gain gratings as well as absorption gratings, fiber gratings, and gratings in frequency selective materials.

Dynamic gratings can also be provided. In the embodiments described above, the gratings are static. The following describes an embodiment wherein the gratings can be dynamically reprogrammed with respect to their spectral filtering functions. In the previously described embodiments, the spectral transfer function of the compound gratings (and segmented gratings) is determined by the parameters A_l, φ_l, x_l, and Λ_l of its constituent subgratings. Generally speaking, any means known in the art that provides for dynamic control of one or more of these parameters will enable dynamic reprogramming of gratings. A variety of construction methods allow for dynamic reconfiguration of gratings, for example, control of φ_l and A_l through control of substrate or overlay index of refraction. A grating created by the means described above may be overlaid with a material whose index of refraction can be controlled by any of the standard means known in the art including, for example, applied electric field, pressure, current, or optical irradiation. If the means of controlling the refractive index of the overlayer is applied to act differentially over spatial regions essentially coinciding with the subgratings comprising the grating, either φ_l or A_l can be controlled. To control φ_l alone, an overlayer may be applied to the side of the substrate opposite to the grooves. Variation in optical thickness in the overlayer induced by any means known in the art then allows one to vary φ_l. If the overlayer is applied to the groove side of the grating (filling in the grooves), then both φ_l and A_l can be controlled. A_l may be controlled by changing the difference in refractive index between the grooves and the overlayer. φ_l can be controlled by controlling the optical path length of the overlayer (as in the case when the overlayer is applied on the substrate side opposite the grooves). The ratio $\Delta A_l/\Delta\varphi_l$ may be varied by adjusting the thickness of the overlayer. Here ΔA_l ($\Delta\varphi_l$) is the change in A_l (φ_l) introduced by a given change in refractive index of the overlayer. Control of A_l alone can be achieved by a variety of means including the addition of overlayers on both sides of the grating substrate and configuration of the overlayers so that the optical path difference introduced by index changes of the two layers cancels and thus so does the change in φ_l. On the other hand, the change in amplitude of the phase subgratings is sensitive to the index change of only one of the overlayers and does not cancel. Pure A_l control can also be obtained by stacking two differentially controlled overlayers on the groove side of the grating. Again, the optical path difference on passing through both layers is constrained to be constant.

The complex φ_l can also be controlled through control of substrate or overlay transmission. We reinterpret $h_l(x')$ in Eq. (1) to define the generalized complex amplitude transmission function of a grating to be given by:

$$H_i(x') = \exp(jh_i(x')) \quad (5)$$

In this representation we allow $h_i(x')$ to be complex in order to include gain or absorption gratings in the above presented treatment. When the amplitude factor A_i is considered to be complex, the imaginary part subsequently describes the loss or gain grating amplitude. Furthermore, by generalizing φ to be a complex number, we include the possibility of subgrating absorption or gain introduced by a variation in substrate transmission or a superimposed amplitude mask.

A grating, as described earlier, may be overlaid with a material whose optical intensity transmission can be controlled by any of the standard means known in the art including, for example, with a liquid-crystal amplitude modulator or an electro-absorptive material. If the means of controlling the transmission of the overlayer is applied to act differentially over spatial regions essentially coinciding with the subgratings comprising the segmented grating, the imaginary part of φ can be controlled. Changing φ will effect a change in the transfer function T(v) as described in Eqs. (1-4).

In the communication system shown in FIG. 1A, two optical channels are multiplexed using OCDMA coding. As illustrated in FIG. 9, additional channels can be encoded, multiplexed, transmitted and then demultiplexed. In the embodiment shown in FIG. 9, four channels 901, 902, 903 and 904 are modulated by modulators 901a-904a, multiplexed by a compound grating 919, transmitted on a fiber 911, demultiplexed by a compound grating 919a, and then detected by detectors 901d-904d. The compound gratings 919, 919a comprise four superimposed segmented gratings of the type previously described.

While the invention has been described with respect to embodiments thereof, it will be understood by those skilled in the art that various changes in format and detail may be made without departing from the spirit and scope of the invention.

We claim:

1. An apparatus that applies a predetermined complex-valued spectral transfer function to an input optical field producing a filtered field that propagates in an output direction, the apparatus comprising a plurality of spatially distinct subgratings, each subgrating including a periodic array of diffraction elements.

2. The apparatus of claim 1 wherein each of the subgratings has an amplitude, spatial phase shift, a spatial period, and an optical phase shift (A_i, x_i, Λ_i, φ_i, respectively) introduced by a variation in a substrate thickness or a superimposed phase mask, and wherein the amplitude and phase parameters of each of the subgratings for applying the complex-valued spectral filtering function $T(\nu)$ is determined according to the equation

$$a_i = \beta d \int_{m/(\beta\Lambda)-1/(2\beta d)}^{m/(\beta\Lambda)+1/(2\beta d)} \frac{T(\nu)}{F_i(\nu)} \exp(-j\pi(\nu\beta - m/\Lambda_i)(x_i^a + x_i^b))d\nu$$

wherein j is the square root of -1, m is a diffraction order, ν is a frequency of the input optical field, $F_i(\nu)$ is a spatial Fourier transform of a subgrating, $\beta = (\sin\theta_{in} + \sin\theta_{out})/c$, where c is the vacuum speed of light and θ_{in} and θ_{out} are angles between a direction of propagation of the input optical field and the filtered optical field and a line normal to the subgrating, respectively, d is a subgrating width, A_i is determined by an amplitude of a_i, and x_i and φ_i are determined by a phase of a_i.

3. The apparatus of claim 1, wherein the subgratings are situated so as to apply the predetermined spectral transfer function to the input optical field.

4. The apparatus of claim 1, wherein the respective amplitudes of the various subgratings control the spectral transfer function.

5. The apparatus of claim 1, wherein the subgratings have an optical thickness and are defined on a substrate having a thickness, the optical thickness of the subgratings controlled by variation in substrate thickness.

6. The apparatus of claim 1, further comprising an active device that dynamically changes a subgrating parameter including a subgrating optical thickness, a subgrating transmission, and a subgrating placement to dynamical reprogram the subgrating to correspond to the spectral transfer function.

7. The apparatus of claim 1, wherein the subgratings are transmissive gratings.

8. The apparatus of claim 1, wherein the subgratings are reflective gratings.

9. The apparatus of claim 1, wherein the subgratings comprise a planar surface.

10. The apparatus of claim 1, wherein the subgratings comprise a non-planar surface shaped so as to map the input optical field onto a desired output spatial wavefront.

11. An optical device that applies a specified complex-valued spectral filtering function to an input optical field and produces a filtered version of the input field that propagates in an output direction, the filtered output having a temporal structure essentially matching a reference optical waveform, the device comprising a plurality of subgratings combined to form a segmented grating, the segmented grating having a spectral transfer function predetermined according to a the reference optical waveform.

12. An optical device that applies a specified complex-valued spectral transfer function to an input optical field and produces a filtered output that propagates in an output direction, the filtered output having a temporal structure essentially matching a cross-correlation of the input optical field with a reference optical waveform, the device comprising a plurality of subgratings combined to form a segmented grating with a transfer function determined by the reference optical waveform.

13. An optical communication system that multiplexes and demultiplexes a plurality of optical signals in accordance with a set of reference optical waveforms, each reference optical waveform comprising a sequence of time slices, the communication system comprising:

a compound grating that includes at least a first segmented grating, the first segmented grating having a spectral transfer function determined by subgrating parameters A_i, φ_i, x_i, Λ_i that are selected to match a predetermined reference optical waveform, the compound grating multiplexing multiple optical data streams by directing each optical data stream onto to a specific segmented grating along its operative input direction thereby producing an output beam encoded according to the reference optical waveform encoded in the first segmented grating; and

a demultiplexer for demultiplexing a time-code multiplexed optical data stream from an OCDMA channel by directing the OCDMA channel along an input direction of a segmented grating encoded so as to direct the time-code multiplexed optical data stream in a time-code specific output direction.

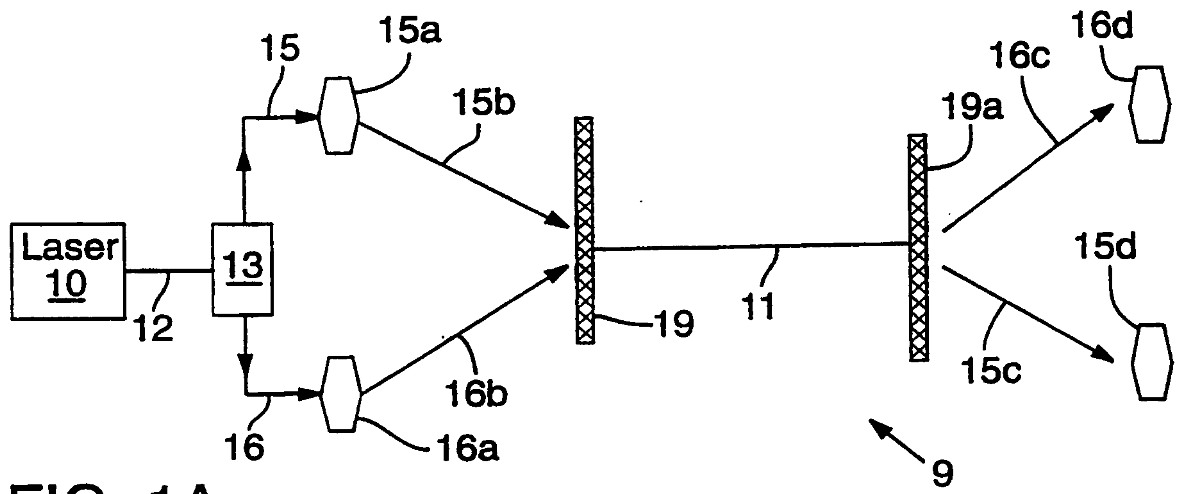
14. A method of applying a selected complex-valued spectral filtering function to light in an input optical field, comprising:

directing the input optical field to a grating structure comprising a plurality of spatially distinct subgratings, each subgrating possessing a periodic array of diffractive elements; and

selecting and combining the subgratings to form a segmented grating corresponding to the selected complex-valued spectral filtering function.

15. A method of applying a predetermined temporal waveform to an input optical field, comprising directing the input optical field to a compound grating that includes a plurality of spatially distinct subgratings, each subgrating including a periodic array of diffractive elements, the subgratings combining to form a segmented grating programmed to produce the predetermined temporal waveform.

16. A method of applying a predetermined complex-valued spectral filtering function to an input optical field, comprising directing the input optical field through a grating structure that includes a plurality of spatially distinct subgratings, each subgrating including a periodic array of diffractive elements, the subgratings combining to produce a transfer function corresponding to segmented grating having a transfer function corresponding to a complex-conjugate of a Fourier spectrum of a reference optical waveform, whereby an output optical field is produced in a predetermined direction having a temporal structure determined by a cross-correlation of the reference optical waveform and the input optical field.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15
15b
16d
16c
19a
Laser
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13
12
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11
15d
15c
16b
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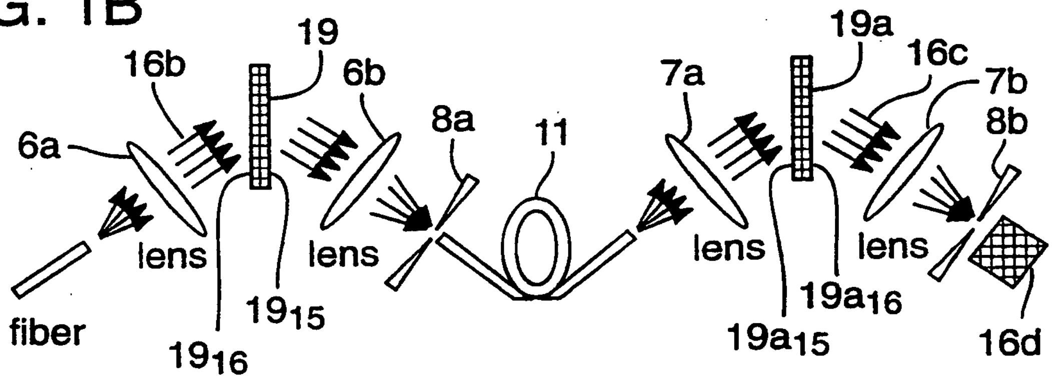
9

FIG. 1A

FIG. 1B


19
16b
6b
6a
8a
11
lens
lens
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19 16
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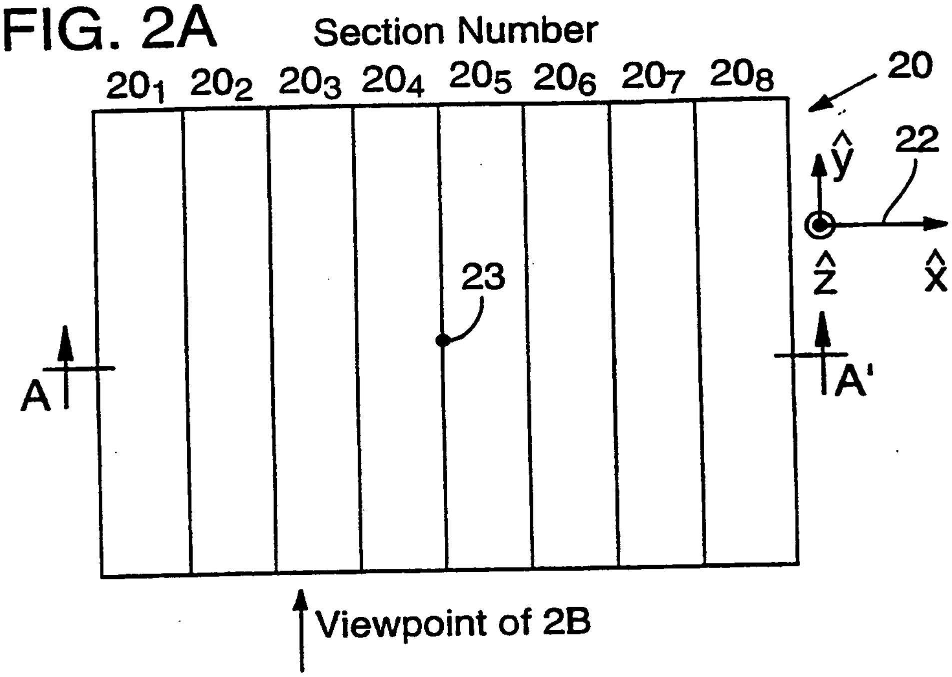
lens
lens
19a 16
19a 15
16d

FIG. 2A


Section Number
20₁ 20₂ 20₃ 20₄ 20₅ 20₆ 20₇ 20₈
20
22
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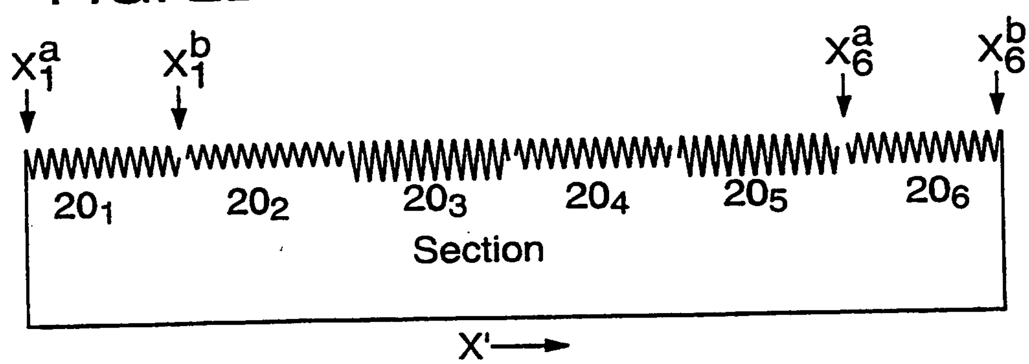
x̂
23
A
A'
Viewpoint of 2B

FIG. 2B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X_1^b
X_6^a
X_6^b
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Section
X'

FIG. 3A

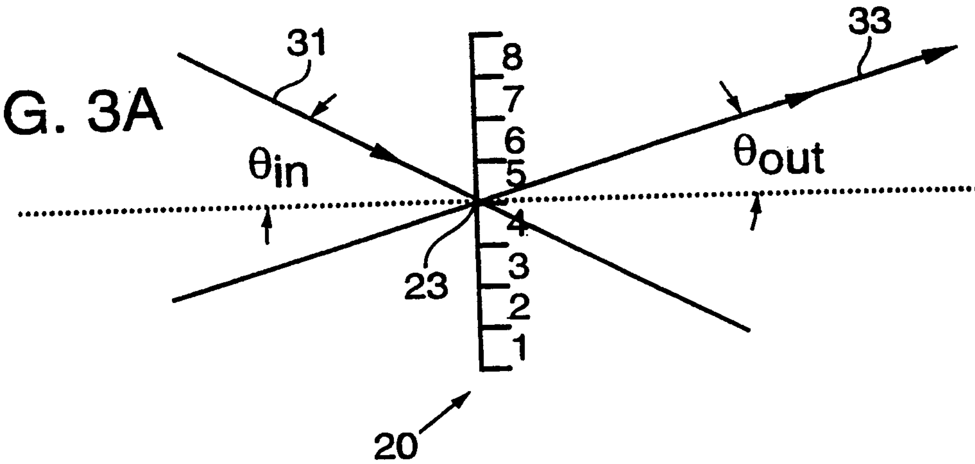


FIG. 3B

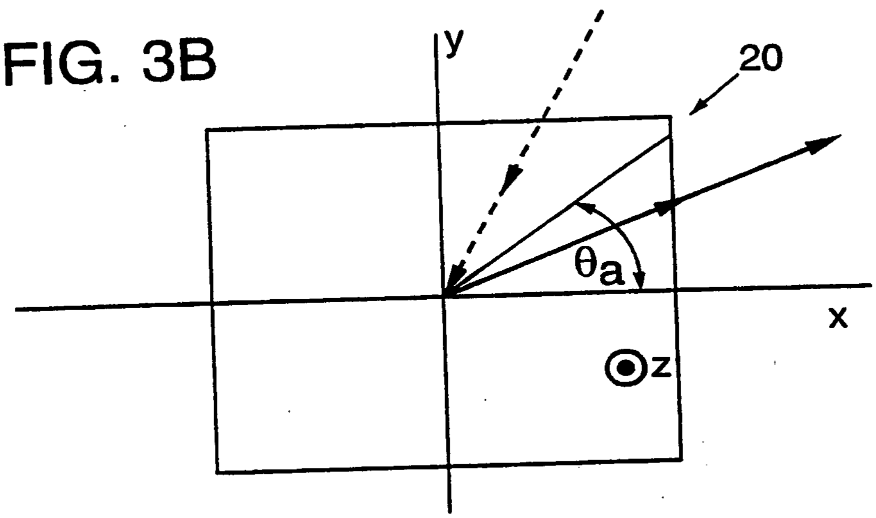
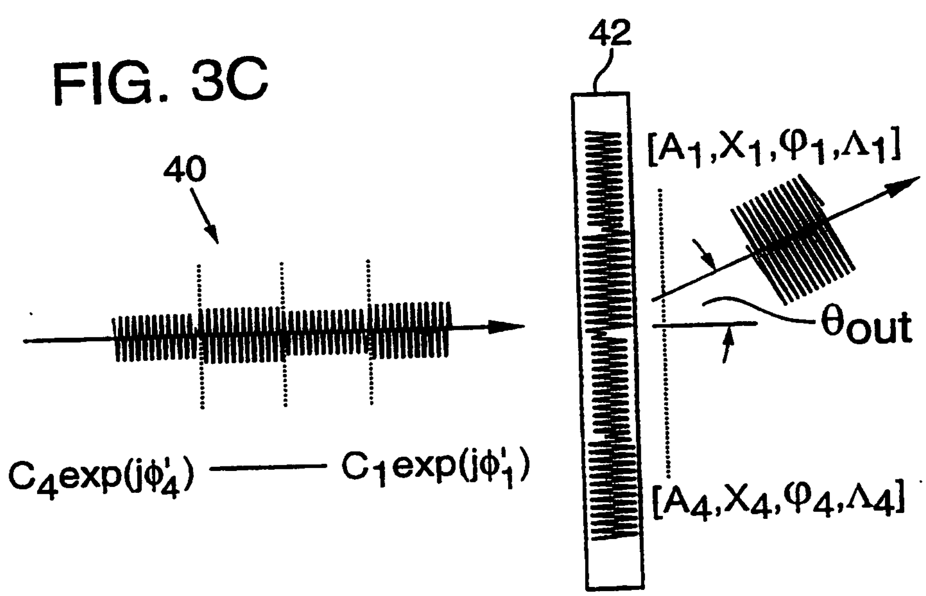


FIG. 3C



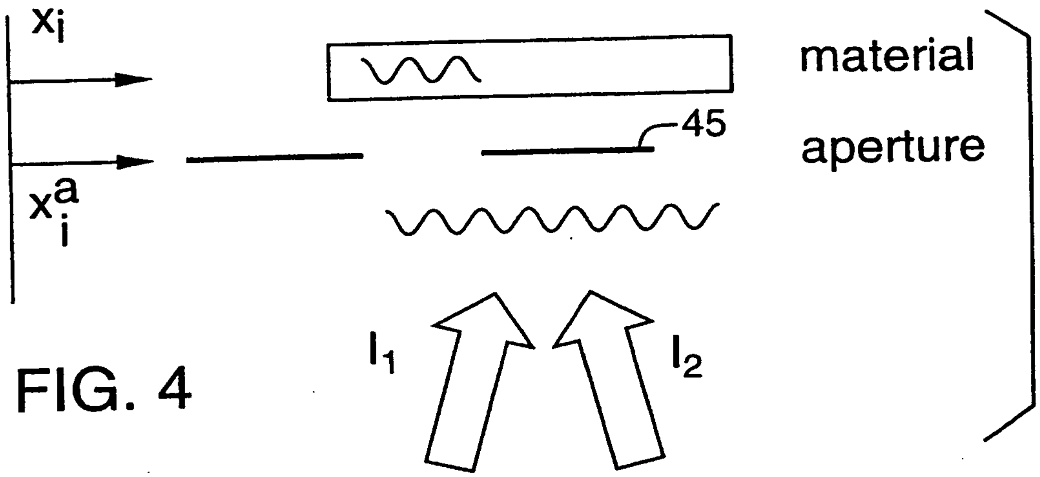


FIG. 4

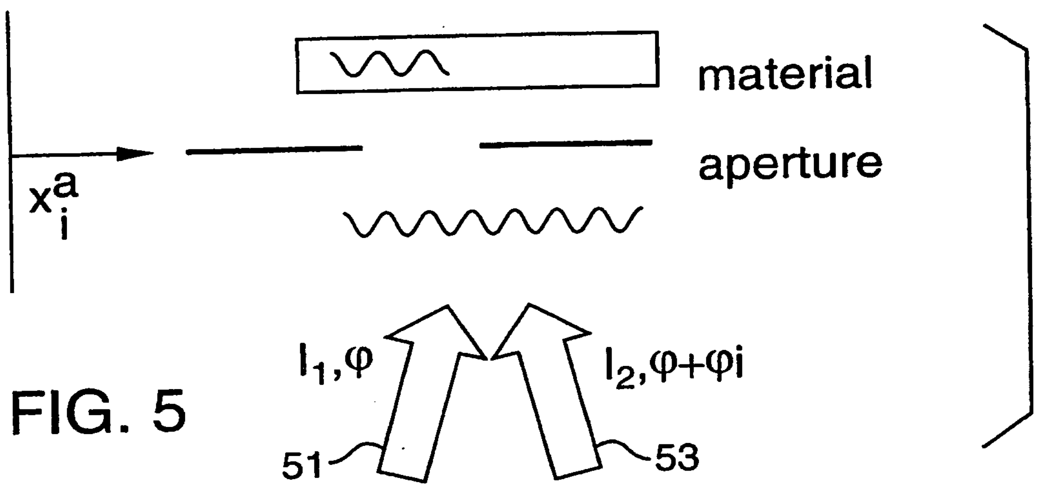


FIG. 5

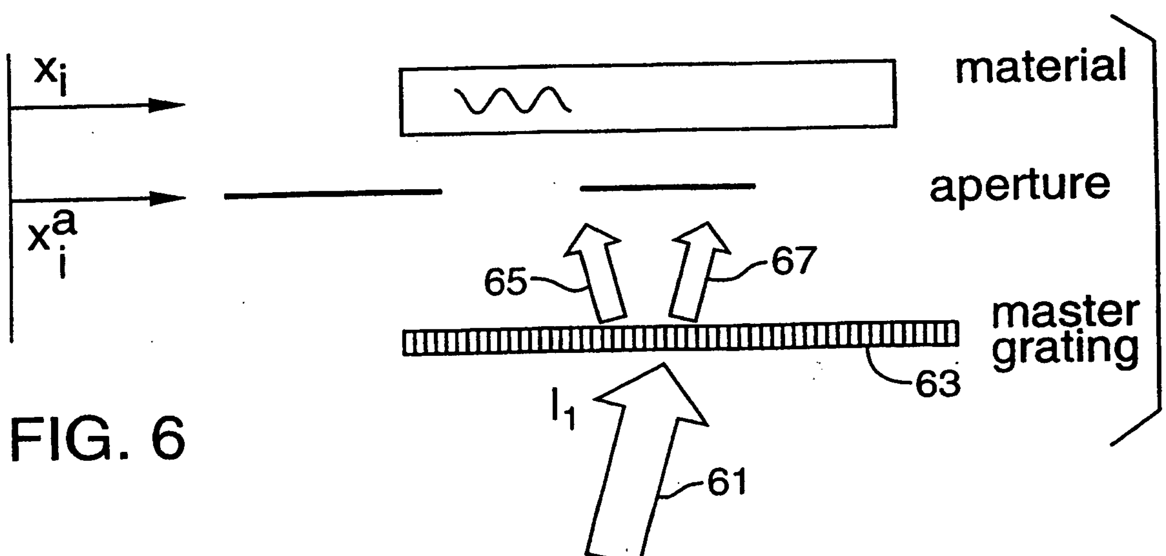


FIG. 6

FIG. 7

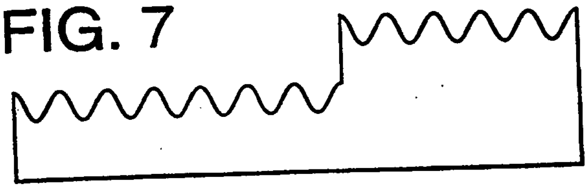
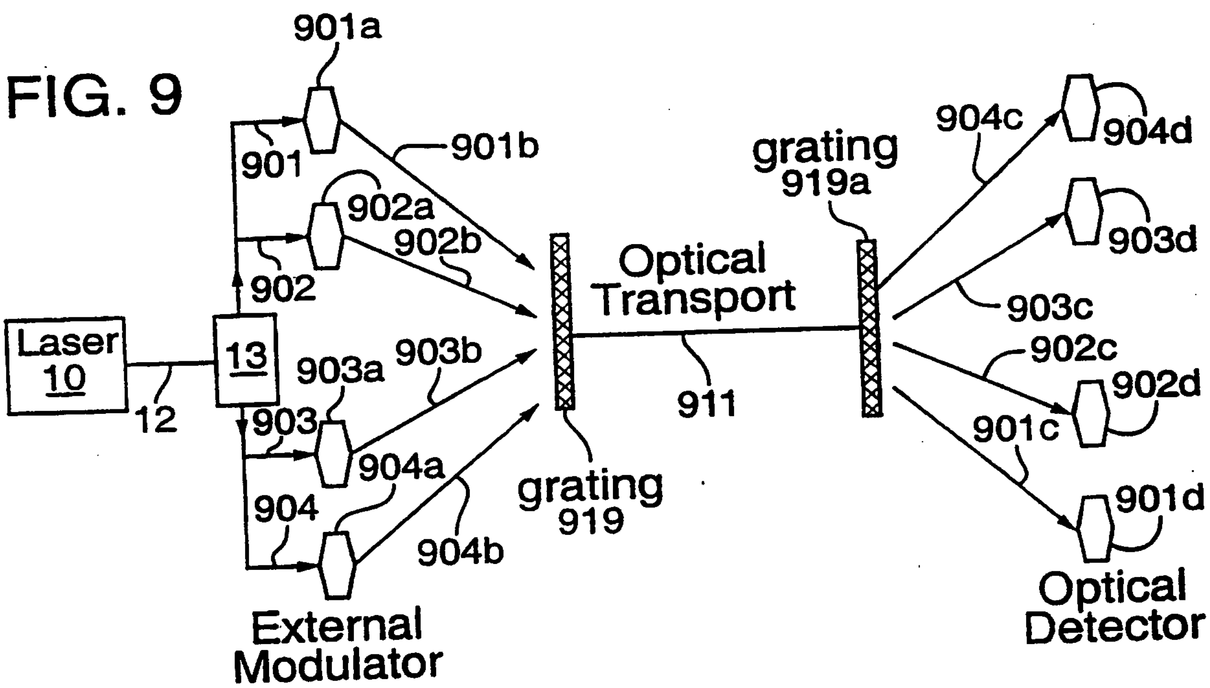


FIG. 8

FIG. 9



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/07391

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G02B 5/18
US CL : 359/569
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/558, 566, 569

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

U.S. PTO APS MESSENGER (USPTO)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A, P	US 5,812,318 A (BABBITT et al.) 22 September 1998 (22.09.98) ALL	1-16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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- "&" document member of the same patent family

Date of the actual completion of the international search

10 AUGUST 1999

Date of mailing of the international search report

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